**The High-Q Approach Notch Filter Design for 60 GHz Collective Thomson Scattering System**

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**Abstract**

This manuscript presents the design and implementation of a high-performance waveguide-based notch filter centered at 60 GHz, tailored for use in Collective Thomson Scattering (CTS) diagnostics systems on next generation burning plasma device in China. The filter features an ultra-narrow notch bandwidth (<0.4 GHz) and achieves over 90 dB rejection at the target frequency, significantly outperforming conventional designs with ~ 2 GHz bandwidth. By employing optimized cylindrical cavity resonators and precise waveguide aperture tuning, the filter maintains minimal insertion loss across the passbands (56-59.8 GHz and 60.2-64 GHz), ensuring full coverage of the ion temperature-dependent scattering spectrum. The design's high quality factor (Q) and robust performance, validated through electromagnetic simulations, make it ideal for protecting sensitive nanowatt-level receivers from multi-megawatt gyrotron interference. Practical implementation considerations, including compatibility with WR-15 waveguides and modular integration, highlight its suitability for next-generation fusion diagnostics. This work advances millimeter-wave filter technology, offering a reliable and scalable solution for high-precision plasma measurements in demanding fusion environments.

**Keywords:** Notch Filter, Electron Cyclotron Heating Protection, High Quality Factor

**1 Introduction**

Millimeter-wave diagnostics [1] are widely employed for measuring essential parameters in magnetic confinement fusion facilities, utilizing both active [2][3] and passive[4][5] methods to provide equilibrium profiles and fluctuations of density [6][7], temperature[8][9][10], magnetic fields [11] and particle velocity distributions [12][13]. Cutting-edge millimeter-wave (mm-wave) and terahertz (THz) technologies, including system-on-chip semiconductor integrated circuits [14][15][16], synthetic modeling[17][18][19], machine learning[20], and real-time feedback control[21][22], have been successfully applied in plasma diagnostics. These advancements have significantly contributed to magnetic confinement fusion research, supporting applications ranging from high-power gyrotrons for plasma heating to ultra-sensitive receiver sensors [23][24]. *The millimeter-wave Collective Thomson Scattering (CTS) diagnostics[25] is an essential system for probing burning plasmas in current experimental fusion devices, as shown in Fig. 1. By analyzing the Doppler-shifted spectrum of scattered millimeter-wave signals, CTS provides access to both electron density fluctuations and ion kinetic properties. The spectral width and asymmetry encode information about the ion temperature and velocity distribution: thermal broadening reflects the ion temperature, while frequency shifts relative to the probing wave indicate bulk plasma flow. In addition, modifications of the spectral shape by energetic ions enable the study of fast-ion dynamics. Compared with density fluctuation measurements, however, extracting ion temperature and velocity distribution is significantly more demanding, requiring higher spectral resolution, accurate calibration, and effective suppression of stray radiation. Despite these challenges, CTS remains a powerful non-invasive diagnostic for magnetically confined plasmas such as tokamaks and stellarators, supporting studies of energy confinement, transport processes, and fast-ion behavior.* This non-invasive method is particularly useful in magnetically confined plasmas, like tokamaks and stellarators, aiding in the understanding of energy confinement, transport processes, and fast ion behavior. In mm-wave CTS diagnostics on next generation burning plasma devices, a 1 MW gyrotron operating at 60 GHz serves as the transmitter, while highly sensitive mm-wave receivers require protection from stray interference. *Frequency-selective surface (FSS) quasi-optical notch filters have been previously deployed, offering about 60 dB attenuation at the gyrotron frequency [26]. Such filters are still applicable to CTS measurements, but they suffer from several drawbacks, including relatively large size, complicated installation, high fabrication difficulty at higher frequencies, limited thermal robustness, and noticeable insertion loss. To address these issues and meet the demands of future fusion pilot plants, a newer waveguide-based notch filter approach[27][28] is being developed as an alternative. The waveguide design provides superior protection and compact integration, with advantages of high fabrication yield, low insertion loss, and greater tolerance to stray high-power radiation. This filter, designed for a V-band (55–65 GHz) plasma diagnostics receiver module, exhibits strong rejection near 60 GHz, is compatible with WR-15 standard waveguides, and can be directly installed between the receiving feedhorn and the semiconductor receiver circuit. Furthermore, by optimizing the filter geometry, a high-Q response is achieved, which is particularly important for precise ion kinetic measurements with CTS. These innovations improve both reliability and integration, providing a more robust solution for high-resolution measurements in next-generation fusion experiments.*

Diagram of a laser beam

Description automatically generated

*Figure 1. The overview of 60 GHz Collective Thomson Scattering system.*

Millimeter-wave CTS diagnostics relies on advanced SoC receiver designs and robust gyrotron radiation protection, as detailed in Section 2. Key to this protection is a high-performance waveguide notch filter, designed for the V-band (55–65 GHz) to attenuate stray 60 GHz gyrotron radiation while preserving diagnostic signals. Section 3 presents the technical implementation of this WR-15 waveguide filter, emphasizing its compact integration with plasma-facing receivers. Section 4 explores filter optimization via electromagnetic simulations, including power handling tests critical for megawatt-level gyrotron environments. The filter achieves >90 dB rejection at 60 GHz and complies with fusion pilot plant requirements for modularity and reliability. Section 5 concludes with a summary of the design’s viability for future CTS systems in burning plasma experiments.

**2 Delicate receiver protection requirements**

The 60 GHz millimeter-wave CTS system currently under construction for burning plasma devices represents a critical diagnostic tool for measuring key plasma parameters. By analyzing scattered signals across different frequency bands, this system will provide radially resolved measurements of both ion temperature (58-62 GHz range) and deuterium-tritium fuel ratio (56-64 GHz range). The diagnostic employs a high-power gyrotron transmitter that injects a 60 GHz beam obliquely through the upper mid-plane port, with the scattering volume determined by the intersection of transmitter and receiver beams as shown in Fig. 2. The extreme sensitivity requirements pose significant technical challenges for receiver development. Due to the small scattering cross-section, the system must detect nano-watt-level signals while maintaining an acceptable signal-to-noise ratio. This demands a receiver module with exceptional performance characteristics: high conversion gain, ultra-low electronic noise, and compact system-on-chip integration. Our development focuses on creating such a receiver capable of resolving both the narrowband ion temperature signals and broader D-T ratio (deuterium - tritium ratio) spectrum.

A major operational challenge comes from protecting this sensitive receiver from multi-megawatt gyrotron reflections[26]. We have developed a custom 60 GHz notch filter that provides over 90 dB of rejection at the transmitter frequency while maintaining minimal insertion loss across the measurement bands. This protection system is crucial for preventing both signal-to-noise degradation and potential receiver damage from high-power interference. The filter's waveguide implementation allows direct integration with the receiver feedhorn and semiconductor circuits, meeting the stringent requirements for fusion pilot plant diagnostics. This integrated CTS system represents a significant advancement in millimeter-wave plasma diagnostics. By combining cutting-edge receiver technology with robust protection systems, we enable reliable measurements of both ion temperature and fuel ratio in burning plasma conditions. The design not only addresses current experimental needs but also provides a scalable solution for future fusion devices, with particular attention to modularity, maintainability, and compatibility with the harsh environment expected in fusion power plants.

The notch filter developed for the 60 GHz CTS receiver represents a significant advancement in plasma diagnostic technology, addressing unique challenges not encountered in conventional systems. Unlike standard plasma diagnostic notch filters that typically feature bandwidths greater than 2 GHz, the CTS application requires an exceptionally narrow stopband of less than 0.4 GHz, based on 60 GHz scattering calculation. This stringent specification must be achieved while maintaining a rejection depth exceeding 90 dB, creating a demanding engineering challenge that pushes the boundaries of millimeter-wave filter design. Achieving this level of performance requires innovative design approaches and careful engineering trade-offs. The filter architecture incorporates multiple resonant structures arranged in a cascaded configuration to achieve the desired narrowband characteristics. To achieve an optimal scattering spectrum with minimal central frequency band loss in CTS diagnostics, a high quality factor Q (as defined by Equation 1) notch filter is required.

(1)

The quality factor Q is defined as the ratio of the resonant frequency *f0* to the 3 dB bandwidth *Δf*, quantifying the resonator's frequency selectivity and energy storage efficiency [29]. Special attention has been paid to manufacturing tolerances, as even minor dimensional variations could significantly impact the filter's performance[30]. The design incorporates tuning elements and compensation features to maintain consistent performance across production units, ensuring high yield and reliability in the demanding fusion environment.



*Figure 2. Transmitter and receiver beam characterizations of 60 GHz CTS system.*

**3 Novel notch filter design with narrow notch bandwidth**

The notch filter employs cylindrical resonant cavities to achieve selective attenuation at the target frequency of 60 GHz. Figure 3 illustrates the fundamental design concept, where a cylindrical cavity is orthogonally coupled to a standard rectangular waveguide (WR-15). This 90° orientation between the cavity axis and the TE10 (Transverse Electric 10) mode polarization enables efficient power transfer from the waveguide's dominant mode to the cylindrical cavity's TE111 mode, creating the desired frequency-selective characteristics.



*Figure 3. The 3D structure of the signal stage cavity in the 60 GHz notch filter approach.*

For this high-Q 60 GHz notch filter implementation, the cavity height h is strategically aligned with the WR-15 waveguide's longer dimension to ensure mechanical compatibility and minimize fabrication complexity [31]. The axial mode number is fixed at p = 1, the lowest odd integer, in order to meet two essential constraints: (1) Even-valued p modes inherently exhibit a central electric field null, preventing effective excitation due to symmetry mismatch with the feed structure; (2) Higher odd modes (p ≥ 3) would require operating frequencies exceeding the target 60 GHz band. With h and p defined, the TE111 mode’s wavelength is analytically determined using the transcendental equation governing cylindrical resonators, where the radius resolves from the first root of the Bessel function derivative J₁’(x11) = 0 (x11 ≈ 1.8412). Full-wave simulations validate the derived diameter D ≈ 3.92 mm, demonstrating stable Q > 150, within ± 0.03 mm manufacturing tolerance. This systematic approach decouples mechanical and electromagnetic constraints, enabling predictable high-frequency resonator realization.

The rectangular coupling slot serves as the critical interface between waveguide and cavity. We maintain identical heights for both slot and cavity to reduce machining complexity and improve production yield. Numerical simulations guided the slot depth optimization for optimal 60 GHz coupling. Notably, our parametric study reveals that slot width significantly affects rejection bandwidth. While narrower slots (0.2-0.3 mm range) provide better selectivity (reducing 3 dB and 20 dB bandwidths), they present substantial manufacturing challenges. Balancing performance with practicality, we selected a slot width of 0.4 mm, achieving 60 dB attenuation across 59.96 - 60.05 GHz while maintaining manufacturability.

The filter's performance is enhanced through multiple cascaded cavities. The number of cavities trades off between rejection performance (depth and steepness) and fabrication complexity. Inter-cavity spacing follows quarter-wavelength impedance matching principles (Equation 2):

g = (2n+1)λg/4 n = 1, 2, 3,… (2)

where λg is the guided wavelength in the rectangular waveguide. For our WR-15 implementation (1.8796 × 3.7592 mm cross-section) at 60 GHz (λg = 8.36 mm), we optimized the gap distance to 5.02 mm (n = 2) to minimize insertion loss and overall footprint while ensuring practical manufacturability. This multi-cavity approach provides the necessary rejection characteristics to protect sensitive millimeter-wave diagnostics from 60 GHz gyrotron interference while maintaining acceptable passband performance.

**4 Performance and robustness**

The primary function of 60 GHz high-Q waveguide notch filter is to protect the extremely sensitive nanowatt-level receiver from potential damage caused by electron cyclotron heating (ECH)[32] leakage or other parasitic coupling paths from the vacuum vessel. The filter's performance requirements demand both strong rejection at the gyrotron frequency and minimal impact on the diagnostic signal bands.

After evaluating various design configurations, an eight-cavity architecture was selected as the optimal balance between filter performance and fabrication complexity. As shown in Fig. 4, the cavities are precisely arranged with an optimized inter-cavity spacing of 5.03 mm within the standard WR-15 waveguide framework, resulting in a compact total length of approximately 20.12 mm. Extensive numerical simulations were conducted to determine the ideal cavity parameters, ultimately settling on a diameter of 3.92 mm that provides excellent rejection characteristics across the required 60 ± 0.2 GHz band while maintaining structural integrity.



***Figure 4.*** *The 60 GHz notch filter consists of multiple stage cavities combined, featuring a unit length of 5.03 mm.*

The coupling slots between cavities were carefully optimized to 0.4 mm width, 3.76 mm height, and 1.4 mm depth, achieving the necessary coupling quality while considering manufacturing tolerances. Figure 5 presents the simulated performance results from CST Studio Suite [33], showing the electric field distribution of the fundamental mode at 60 GHz in the copper construction (σ = 5.8 × 10⁷ S/m). As shown in Fig. 6, the simulations demonstrate exceptional performance characteristics, including greater than 120 dB attenuation at the center frequency with a 3 dB rejection bandwidth of 0.39 GHz. Importantly, the filter maintains excellent passband performance from 56 - 64 GHz with less than 1 dB insertion loss, ensuring minimal impact on the critical CTS diagnostic signals while providing robust protection against high-power interference.



*Figure 5. Power loss in beam propagation: (a) High attenuation observed at 60 GHz; (b) Improved transmission efficiency at 64 GHz.*



*Figure 6. Performance of the 60 GHz notch filter: (a) Transmittance spectrum showing <1 dB insertion loss across the passbands (55–59.6 GHz and 60.4–65 GHz). (b) Reflectance below -25 dB in the passband. (c) A 3 dB bandwidth of 0.39 GHz. (d) Detailed reflectance characteristics between 59–61 GHz.*

In burning plasma devices, gyrotrons operating at 105 GHz and 170 GHz are routinely used for auxiliary heating and diagnostics. This multi-frequency operation requires rigorous evaluation of the 60 GHz notch filter's performance across all relevant bands to ensure robust protection for the CTS diagnostic system. As summarized in Table 1, the designed high-Q 60 GHz notch filter exhibits exceptional broadband transmission characteristics at 105 GHz and 170 GHz, with insertion loss better than -3 dB. This performance is critical for system integration, as it mitigates standing-wave formation caused by reflections between cascaded filters targeting distinct frequencies. By maintaining low insertion loss at non-resonant frequencies while delivering deep rejection at 60 GHz, the filter simplifies receiver protection schemes, eliminating the need for complex multi-stage filtering that could compromise signal integrity or introduce additional noise.

*Table 1: Comparative characterization of the 60 GHz notch filter's response at 60 GHz, 105 GHz, and 170 GHz.*

|  |  |  |
| --- | --- | --- |
| **Gyrotron Frequency (GHz)** | **Transmittance (S21)** | **Reflectance (S11)** |
| 60 GHz (CTS transmitter source) | -122 dB | -0.42 dB |
| 105 GHz (another CTS transmitter source) | -0.5 dB | -9.62 dB |
| 170 GHz (Electron Cyclotron Heating source) | -1.24 dB | -6.04 dB |

**5 Summary**

Waveguide notch filters have emerged as a particularly robust solution for safeguarding sensitive microwave diagnostic equipment against harmful gyrotron radiation in fusion plasma experiments. The 60 GHz notch filter developed for this application utilizes an optimized eight-cavity cylindrical resonator configuration that achieves outstanding performance metrics while remaining practical for fabrication and integration. Designed specifically for incorporation into V-band system-on-chip receiver modules, this filter demonstrates exceptional rejection characteristics (>120 dB at the target 60 GHz frequency) while maintaining ultra-wideband transmission properties with minimal insertion loss — an essential requirement for plasma diagnostic applications.

The filter's waveguide implementation provides several important benefits for burning plasma diagnostics. Its standard WR-15 waveguide interfaces allow for direct compatibility with existing millimeter-wave diagnostic systems, facilitating straightforward integration. The simplified mechanical design enhances manufacturability and yield without compromising the precision performance needed for these demanding applications. Notably, the high-Q filtering characteristics provide essential protection for receivers operating at nanowatt sensitivity levels, while the carefully engineered passband ensures unimpeded signal transmission across the required diagnostic frequency ranges.

This balanced design approach successfully addresses the key challenges in plasma diagnostic filter development, simultaneously achieving strong rejection at the target frequency, low passband insertion loss, and practical manufacturability—all important factors for reliable operation in the harsh fusion plasma environment. The standardized interface design enables immediate deployment in current diagnostic setups while providing robust protection against multi-megawatt gyrotron radiation, making this solution particularly valuable for ongoing and future fusion research initiatives.

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**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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